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$b \to s\gamma$ and $Z \to b\bar{b}$ in Technicolor with Scalars *

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Abstract

We consider the radiative decay $b \to s\gamma$, and the correction to the $Zb\bar{b}$ vertex in technicolor models with scalars. In these models, the scalar develops a vacuum expectation value when the technifermions condense, and the ordinary fermions develop masses via Yukawa couplings. Since the symmetry breaking sector involves both a fundamental scalar doublet and an isotriplet of composite scalars (the technipions), the phenomenology associated with the charged scalars is similar to that found in a type-I two-Higgs doublet model. We show that the correction to the $Zb\bar{b}$ vertex is small over the allowed parameter space of the model in the two limits that we consider, and that there can be large, potentially observable, contributions to the $b \to s\gamma$ branching fraction.

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Disclaimer

1 Introduction

The phenomenology of technicolor models with scalars has been considered extensively in the recent literature [1, 2, 3, 4, 5]. In this class of models, the technifermions and the ordinary fermions both couple to a weak scalar doublet, which replaces the conventional ETC sector. When technicolor becomes strong, and a technifermion condensate forms, the Yukawa coupling of the condensate to the scalar produces a linear term in the scalar potential. As a result, the scalar develops a vacuum expectation value (vev), which is responsible for giving the ordinary fermions mass. It has been shown that models of this type do not produce unacceptably large contributions to K^0-$\overline{K^0}$ or B^0-$\overline{B^0}$ mixing, nor to the electroweak S and T parameters [1, 3, 4]. In addition, the new scalars in the model can be made heavy enough to evade detection, even in the limit where the scalar doublet is assumed to have a vanishing $SU(2) \times U(1)$ invariant mass [3]. Technicolor with scalars is interesting on more general grounds because it can arise as a low-energy effective theory in strongly-coupled ETC (SETC) models [6], providing that some degree of fine-tuning is allowed. This fine-tuning is necessary in any workable SETC model to maintain a sufficient hierarchy between the ETC and technicolor scales [7].

It is the purpose of this letter to consider two other important phenomenological issues that have not been studied in the context of technicolor models with scalars: the correction to the $Zb\bar{b}$ coupling, and the branching fraction $\mathrm{B}(b \to s\gamma)$. In conventional ETC models, it has been shown that there is a reduction in the $Zb\bar{b}$ coupling proportional to m_t, which can decrease $R_b \equiv \Gamma(Z \to b\bar{b})/\Gamma(Z \to \mathrm{hadrons})$ by as much as 5% [8]. In two-Higgs doublet models, and in the minimal supersymmetric standard model, the $Zb\bar{b}$ coupling can shift as a consequence of radiative corrections involving charged scalars that couple b to t through the large top-quark Yukawa coupling. Technicolor with scalars is similar to a type-I two-Higgs doublet model, in which only one scalar doublet (in our case, the fundamental scalar) couples to both the charge 2/3 and charge -1/3 quarks. Unlike the situation in conventional ETC models, the main correction to the $Zb\bar{b}$ coupling in technicolor models with scalars comes from the radiative effects of the physical charged scalars in the low-energy theory. It is therefore possible to adapt much of the existing analysis of the $Zb\bar{b}$ coupling in two-Higgs doublet models to study the parameter space in the models of interest to us here.

The other process that we consider, $b \to s\gamma$, vanishes at tree-level in the Standard Model due to the GIM mechanism, but can occur at one-loop through penguin diagrams. Since the Standard Model branching fraction depends on small GIM-violating effects, it has been suggested that this decay mode may provide a sensitive probe of physics beyond the Standard Model [9]. The recent measurement by the CLEO collaboration of the inclusive $b \to s\gamma$ decay width has yielded the bound $M_{H^+} > 260$ GeV for the charged scalar mass in type-II two-Higgs doublet models [10]. This gives us substantial motivation to study whether $b \to s\gamma$ can receive important contributions in technicolor models with scalars. Again, existing calculations of the inclusive decay width in type-I two-Higgs doublet models can be modified to enable us to determine the $b \to s\gamma$ width throughout our model's parameter space.

2 The Model

The model that we consider has been described in detail elsewhere [1, 3], so we summarize only the essential components. In addition to the Standard Model gauge structure and particle content, we assume a minimal $SU(N)$ technicolor sector, with two techniflavors that transform as a left-handed doublet and two right-handed singlets under $SU(2)_W$,

$$\Upsilon_L = \begin{pmatrix} p \\ m \end{pmatrix}_L \quad p_R \quad m_R \tag{2.1}$$

and that have the weak hypercharge assignments $Y(\Upsilon_L) = 0$, $Y(p_R) = 1/2$, and $Y(m_R) = -1/2$. The ordinary fermions are technicolor singlets, with their usual quantum number assignments. The technifermions and ordinary fermions couple to a weak scalar doublet which has the quantum numbers of the Higgs doublet of the Standard Model

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \tag{2.2}$$

The purpose of the scalar is to couple the technifermion condensate to the ordinary fermions and thereby generate fermion masses.

What is relevant to the phenomenology that we consider here is that the technipions (the isotriplet scalar bound states of p and m) and the isotriplet components of ϕ will mix. One linear combination becomes the longitudinal component of the W and Z. The orthogonal linear combination remains in the low-energy theory as an isotriplet of physical scalars. Denoting the physical scalars π_p, the coupling of the charged physical scalars to the quarks is given by [3]

$$i(\frac{f}{v})\left[\overline{D_L}V^\dagger\pi_p^- h_U U_R + \overline{U_L}\pi_p^+ V h_D D_R + h.c.\right] \tag{2.3}$$

where V is the Cabibbo-Kobayashi-Maskawa (CKM) matrix, f is the technipion decay constant, and v is the electroweak scale ≈ 250 GeV. Here U and D are column vectors in flavor space, and the Yukawa coupling matrices are diagonal $h_U = diag(h_u, h_c, h_t)$, $h_D = diag(h_d, h_s, h_b)$. Notice that (2.3) has the same form as the charged scalar coupling in a type-I two-Higgs doublet model.

The fact that the quarks couple only to the fundamental scalar, but not to the technipions, also accounts for the dependence of (2.3) on f/v. The technicolor scale and the scalar vev, which we will call f', both contribute to the electroweak scale

$$f^2 + f'^2 = v^2 \tag{2.4}$$

In the limit that $f \to 0$, the fundamental scalar vev determines the electroweak scale, and the longitudinal components of the weak gauge bosons are mostly the fundamental scalar. Thus, the physical charged scalars are now mostly technipion in this limit, and we expect their couplings to the quarks to vanish. The couplings in (2.3) have the correct behavior in this limit.

The chiral Lagrangian analysis in Refs. [3, 4] allows us to estimate the mass of the charged scalars. At lowest order, the mass of the physical isotriplet is given by

$$m_\pi^2 = 2c_1\sqrt{2}\frac{4\pi f}{f'}v^2 h \tag{2.5}$$

where h is the average technifermion Yukawa coupling $h \equiv (h_+ + h_-)/2$, and where h_+ and h_- are the individual Yukawa couplings to p and m, respectively. The constant c_1 is an undetermined coefficient in the chiral expansion, but is of order unity by naive dimensional analysis (NDA) [11]. We set $c_1 = 1$

in all numerical estimates to follow. Since we are only working to lowest order, c_1 and h always appear in the combination $c_1 h$; thus the uncertainty in our estimate of c_1 can be expressed alternatively as an uncertainty in the value of h.

The only remaining ingredient that we need for the numerical analysis is the dependence of f and f' on the free parameters of the model. In general, f and f' can depend on h_+, h_-, M_ϕ, and λ, where M_ϕ is the $SU(2)\times U(1)$ invariant scalar doublet mass, and λ is the ϕ^4 coupling. Two limits have been studied previously in the literature: *(i)* the limit in which λ is small and can be neglected [1], and *(ii)* the limit in which M_ϕ is small and can be neglected [3]. One advantage of working in these two limits is that the phenomenology of the model can be described simply in terms of a two-dimensional parameter space, either (M_ϕ,h) or (λ,h). (This is possible because h_+ and h_- enter only through the combination $h = (h_+ + h_-)/2$ at lowest order in the chiral expansion.) In general, the condition that the Higgs field σ (the isoscalar component of ϕ) has no vacuum expectation value

$$V'(\sigma = 0) = 0 \tag{2.6}$$

gives us the constraint

$$M_\phi^2 f' + \frac{\lambda}{2} f'^3 = 8\sqrt{2} c_1 \pi h f^3 \tag{2.7}$$

where the last term is induced by the technicolor interactions [3, 4]. In either limit *(i)* or *(ii)* described above, f and f' can be found by solving (2.4) and (2.7) simultaneously in terms of the two remaining free parameters.

If we also include the largest Coleman-Weinberg corrections to the potential

$$V_{CW} = -\frac{1}{64\pi^2}\left(3h_t^4 + 2Nh^4\right)\sigma^4 \log\left(\frac{\sigma^2}{\mu^2}\right) \tag{2.8}$$

(setting $h_+ = h_-$ for simplicity) and define the renormalized ϕ^4 coupling $\lambda_r = V''''(f')/3$ in order to remove the μ-dependence in (2.8), then the form of (2.7) will remain unchanged providing that we work with the shifted parameters

$$\tilde{M}_\phi^2 = M_\phi^2 + \left(\frac{44}{3}\right)\frac{1}{64\pi^2}\left[3h_t^4 + 2Nh^4\right] f'^2 \tag{2.9}$$

in limit *(i)*, or [3]

$$\tilde{\lambda} = \lambda + \frac{11}{24\pi^2}\left[3h_t^4 + 2Nh^4\right] \tag{2.10}$$

in limit *(ii)*. It is convenient for us to adopt these new parameters because they absorb the effects of the radiative corrections, as far as they affect the phenomenology of the charged scalars. However, the isoscalar mass m_σ will have a different functional dependence on the new parameters. In limit *(i)*

$$m_\sigma^2 = \tilde{M}_\phi^2 + (\frac{64}{3})\frac{1}{64\pi^2}\left[3h_t^4 + 2Nh^4\right] f'^2 \tag{2.11}$$

while in limit *(ii)*

$$m_\sigma^2 = \frac{3}{2}\tilde{\lambda} f'^2 - \frac{1}{8\pi^2}\left[3h_t^4 + 2Nh^4\right] f'^2 \tag{2.12}$$

In this paper we will again study limits *(i)* and *(ii)*, in the interest of completing the phenomenological discussion presented in Refs. [3, 4].

3 Results

Given the couplings in (2.3), and estimating the charged scalar mass, from equations (2.4), (2.5) and (2.7), we can apply previously published two-Higgs doublet model results to study our model in limits *(i)* and *(ii)*. The one-loop effects of charged scalars on the $Zb\overline{b}$ coupling are discussed in Refs. [12, 13]. We adapt the results given in the appendix of Boulware and Finnel [12]. We compute the quantity $\delta R_b/R_b$, where R_b is defined by

$$R_b = \frac{\Gamma(Z \to b\overline{b})}{\Gamma(Z \to \text{hadrons})} \tag{3.13}$$

The contours of constant $\delta R_b/R_b$ are plotted in Figures 1 and 2, for the model in limits *(i)* and *(ii)* respectively. In both cases, we show the parameter space already excluded by B^0-$\overline{B^0}$ mixing (the area below the B-line), and by the constraint $m_{\pi^+} > m_t - m_b$ (the area to the left and below the $m_\pi = m_t - m_b$ line). We assume a Standard Model top quark, with $m_t = 175$ GeV and with no decay to $\pi^+ b$, consistent with the recent CDF results [14]. The $hf' = 4\pi f$ line shown in Figure 1 indicates where the chiral Lagrangian analysis breaks down; above this line, the technifermion current masses are no longer small compared to the chiral symmetry breaking scale, and we can make no claims about the phenomenology. Note, however, that this problematic region is avoided in limit *(ii)*, because this area is already excluded by the constraint of vacuum stability, $m_\sigma^2 > 0$ [3]. The differing form of (2.11) and (2.12) explains why we obtain a strong constraint from the the LEP lower bound [15] on the mass of the light neutral isosinglet scalar in limit *(ii)*, but not in limit *(i)*. In limit *(i)*, one must go to negative values of $\tilde{M}_\phi$ before m_σ becomes in conflict with the LEP limit $m_\sigma > 58.4$ GeV; however, the isotriplet scalars become unacceptably light long before then. In both limits we see that the -1% contour for $\delta R_b/R_b$ is almost contiguous with the B-line, and that $\delta R_b/R_b$ becomes smaller as one moves away from the excluded region in the lower right-hand portion of the plots. Thus, we see that a more dramatic effect corresponding to a larger top quark Yukawa coupling is already precluded by the B^0-$\overline{B^0}$ mixing constraints.

The partial width for $b \to s\gamma$ in two-Higgs doublet models has been computed in Refs. [16, 17] . We adopt the results of Grinstein, Springer, and Wise (GSW) [16] in our analysis. In Figures 3 and 4 we plot contours of constant $\delta\Gamma/\Gamma$, the percent shift in the $b \to s\gamma$ partial width relative to the theoretical prediction in the Standard Model (The Standard Model prediction corresponds to a branching fraction of 2.75×10^{-4} [10]). In terms of the function C_7 defined in GSW, we plot contours of constant

$$\frac{(|C_7(m_b)_{2HD}|^2 - |C_7(m_b)_{SM}|^2)}{|C_7(m_b)_{SM}|^2} \tag{3.14}$$

where $2HD$ here refers to a type-I two-Higgs doublet model. Notice that the contours are roughly parallel to the B-line, and may eventually provide a tighter constraint. The 95% confidence level lower bound found by CLEO corresponds to the -64% contour on the plot, but this statement does not take into account the theoretical uncertainty in (3.14). If we assume that $C_7(m_b)$ can be calculated to within 15%, as is suggested in [16], and we assume, conservatively, that (3.14) is known within 30%, then the region absolutely excluded in our model lies below the -83% contour. This boundary is almost contiguous with the B-line, and does not eliminate any additional parameter space. What is interesting is that there is plenty of parameter space in which the correction to $b \to s\gamma$ is significant, (between -1% and -50%) yet not in conflict with the lower bound on $\Gamma(b \to s\gamma)$ found by CLEO. In addition, the region of the parameter space in which the correction to $b \to s\gamma$ is less than -1% includes the region discussed in Ref. [5] which should include a light, extremely narrow technirho.

4 Conclusions

We have extended the phenomenological analysis of Refs. [1, 3, 4, 5] to include corrections to $b \to s\gamma$ and to the $Zb\bar{b}$ vertex in technicolor models with scalars. We have shown that the correction to R_b is negative throughout the allowed region of our model's parameter space in the limits that we considered, but never larger than -1%. This result is consistent with our expectation that corrections to the $Zb\bar{b}$ coupling are suppressed in SETC models by an increased ETC scale [18]. Since the current experimental measurement is *larger* than the Standard Model prediction by two standard deviations [19], it may still be possible to rule out this model if the Standard Model is ruled out on similar grounds. In addition, we have found sizable corrections to the $b \to s\gamma$ width, yielding a branching fraction that is smaller than the Standard Model expectation. Nevertheless, in both cases our results indicate that stongly-coupled ETC models, of which our model is the low-energy limit, easily survive the current experimental constraints. Unlike the electroweak S and T parameters, the $b \to s\gamma$ branching fraction can be calculated more reliably in these models, giving us relatively definitive predictions. Since the deviation from the Standard Model branching fraction can be sizable in some regions of our model's parameter space, this effect may be observable given improved measurements of the $b \to s\gamma$ inclusive decay width.

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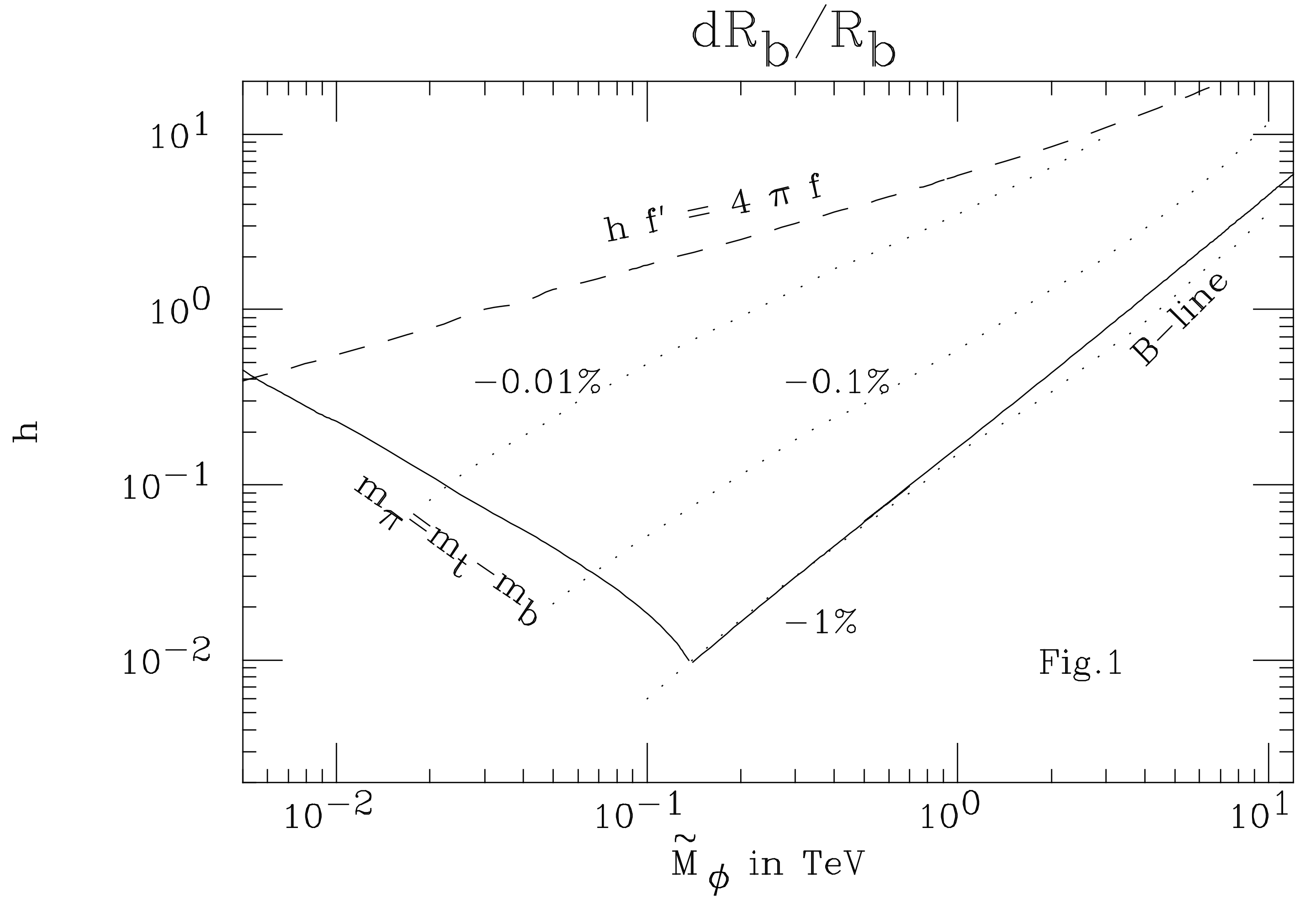
Figure Captions

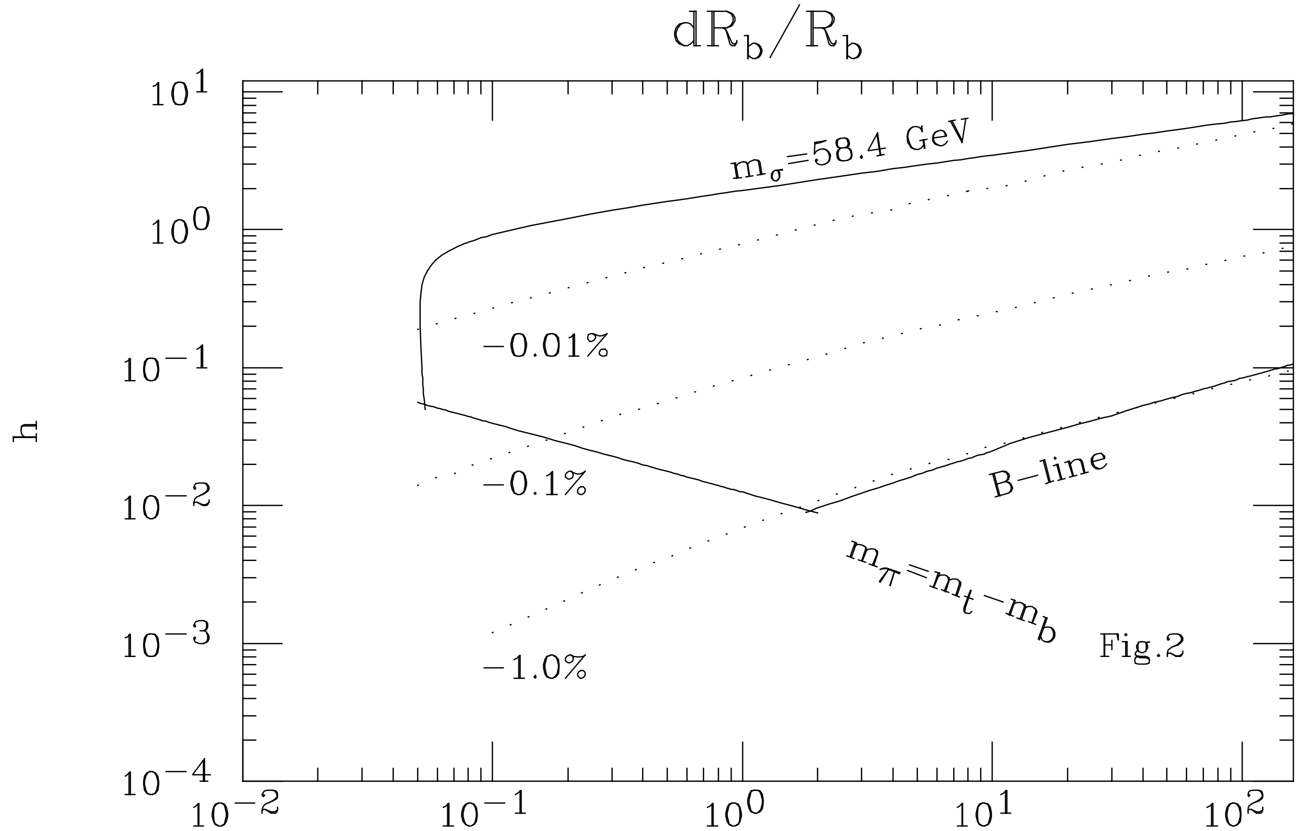
Figure 1: Contours of constant $\delta R_b/R_b$ (dotted lines) in limit *(i).* The allowed region lies above the B-line, and above the $m_\pi = m_t - m_b$ line.

Figure 2: Contours of constant $\delta R_b/R_b$ (dotted lines) in limit *(ii).* The allowed region lies above the B-line, above the $m_\pi = m_t - m_b$ line, and below the $m_\sigma = 58.4$ Gev line.

Figure 3: Percent shift in the $b \to s\gamma$ decay width (dashed lines) in limit *(i)*, relative to the Standard Model prediction. The -100% contour is outside the allowed region, but is provided for reference.

Figure 4: Percent shift in the $b \to s\gamma$ decay width in limit *(ii)*, relative to the Standard Model prediction.


dRb/Rb
h f' = 4 π f
−0.01%
−0.1%
−1%
B−line
mπ=mt−mb
Fig.1
h
M̃φ in TeV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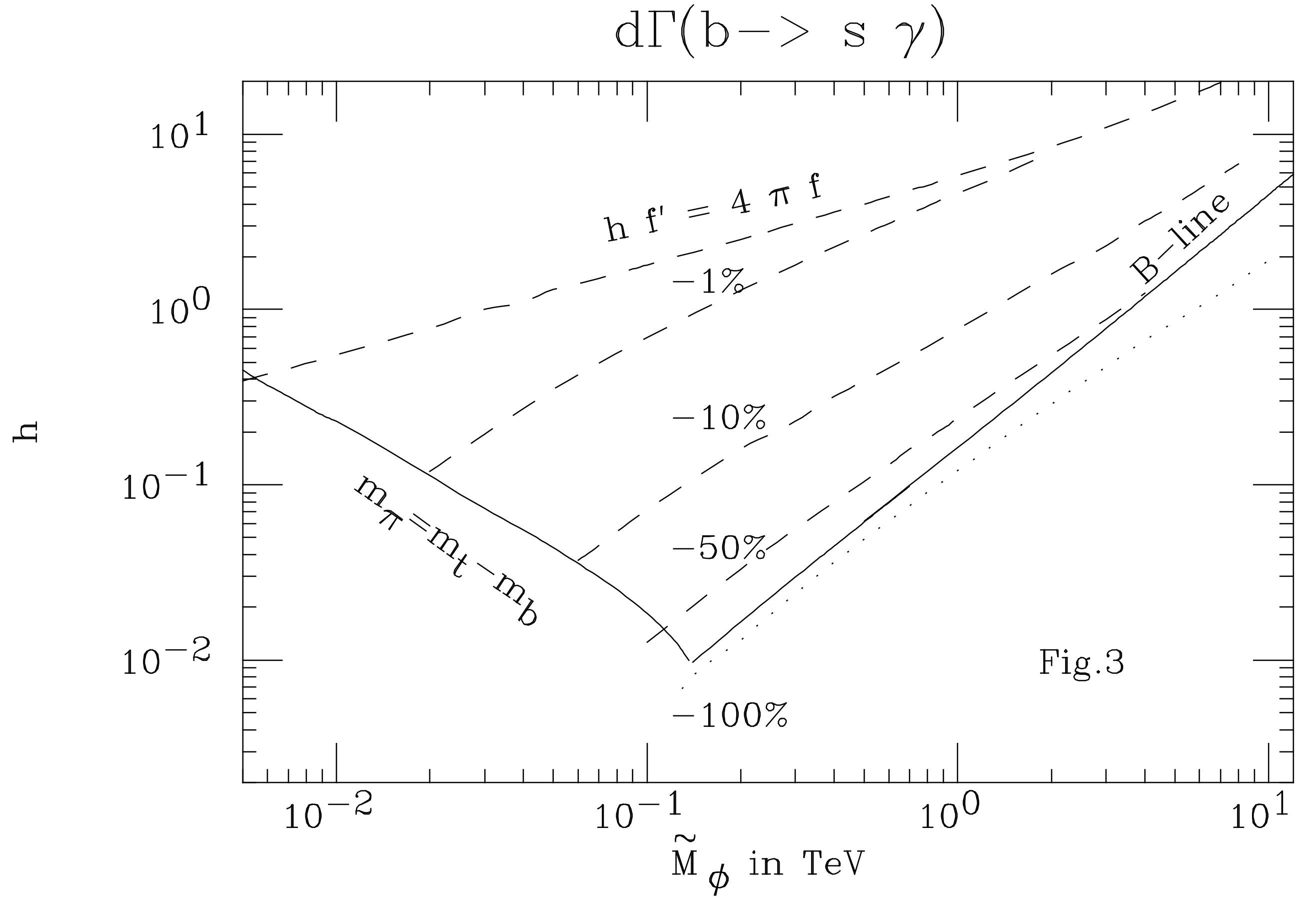
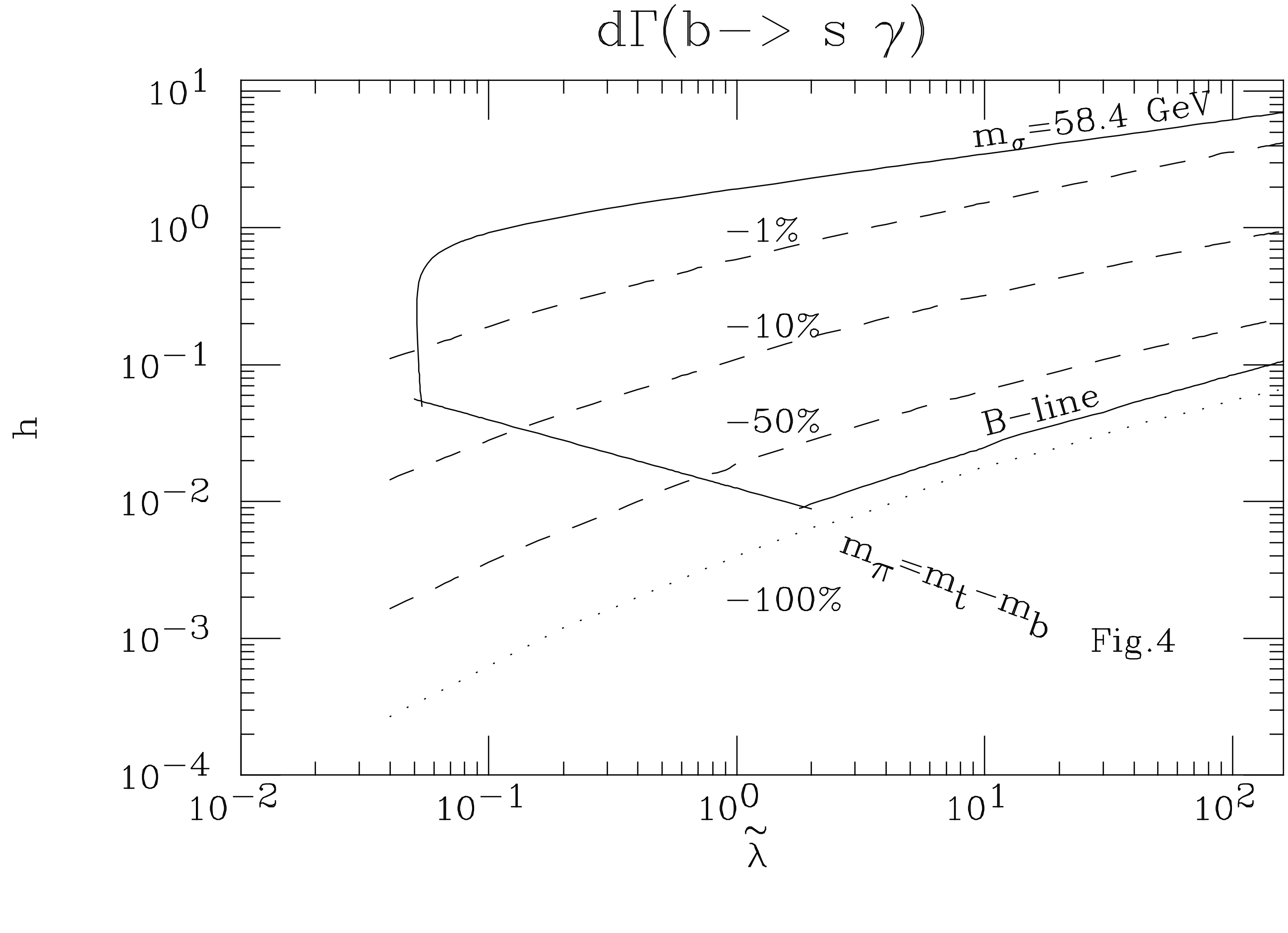
−0.01%
−0.1%
−1.0%
B−line
mπ=mt−mb
Fig.2
h
λ̃



dΓ(b−> s γ)
h
h f' = 4 π f
−1%
−10%
−50%
−100%
B−line
$m_\pi = m_t - m_b$
Fig.3
$\tilde{M}_\phi$ in TeV



dΓ(b−> s γ)
h
m_σ=58.4 GeV
−1%
−10%
−50%
−100%
B−line
$m_\pi = m_t - m_b$
Fig.4
$\tilde{\lambda}$